

Non-thermal emission from galaxy clusters: a Pandora's vase for astrophysics

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The existence of cosmic rays and weak magnetic fields in the intracluster volume has been well proven by deep radio observations of galaxy clusters. However a detailed physical characterization of the non-thermal component of large scale-structures, relevant for high-precision cosmology, is still missing. I will show the importance of combining numerical and theoretical works with cluster observations by a new-generation of radio, Gamma- and X-ray instruments.

1 Introduction

Deep radio observations of the sky have revealed the presence of extended (~ 1 Mpc) radio sources in about 50 merging galaxy clusters (see ^{1,2} and references therein). This diffuse radio emission is not related to unresolved radio-galaxies, but rather to the presence of relativistic particles ($\gamma \gg 1000$) and magnetic fields of the order of μGauss in the intracluster volume. The physical mechanisms responsible for the origin of this non-thermal intracluster component are matter of debate (e.g. ^{3,4}), as well as the effects of intracluster cosmic rays (CRs) and magnetic fields on the thermodynamical evolution and mass estimate of galaxy clusters (e.g. ^{5,6}). A deep understanding of the evolutionary physics of *all* the different cluster components (dark matter, galaxies, thermal and non-thermal intracluster medium – ICM) and of their mutual interactions is indeed essential for high-precision cosmology with galaxy clusters ⁷.

In the following, I will give an overview of our current knowledge of the non-thermal component of galaxy clusters. I will also stress the importance of a new generation of multi-wavelength telescopes – such as the *Low Frequency Array* (LOFAR), and the Gamma- and hard X-ray (HXR) satellites *Fermi* and *NuSTAR* – for a deep understanding of the non-thermal cluster physics. The ΛCDM model with $H_0=70 \text{ km s}^{-1}\text{Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ has been adopted.

2 The discovery of the non-thermal intracluster component: radio observations

The presence of intracluster CR electrons (CRes) and magnetic fields was pointed out in 1970 by Willson ⁸, whose detailed radio analysis of the Coma cluster followed the first detection in 1959 of a noticeably diffuse cluster radio source – Coma C – by Large et al. ⁹.

Diffuse cluster radio sources are very elusive. On the one hand their low-surface brightness ($\sim \mu\text{Jy/arcsec}^2$ at 1.4 GHz) requires low angular resolution observations in order to achieve the necessary signal-to-noise ratio. On the other hand complementary high-resolution observations are needed in order to identify and remove emission from point sources. Samples of clusters hosting diffuse radio sources started to be available from the 90's (e.g. ¹⁰), with the advent

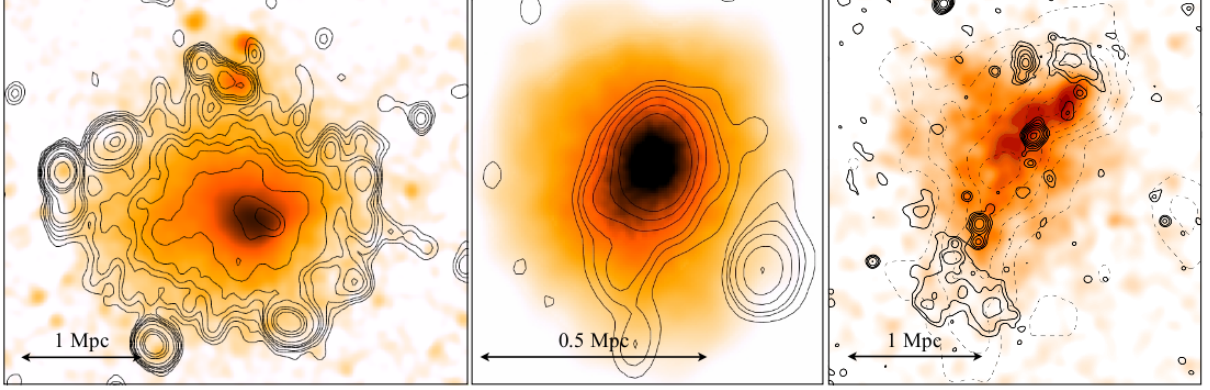


Figure 1: The galaxy clusters Abell 2163 (left), RX J1347.5-1145 (middle) and ZwCl 2341.1+0000 (right) observed in X-rays (brown scale image) and at radio wavelengths (solid contours) (adapted from ^{15,16,18}). A2163 is the hottest Abell cluster and it hosts one of the most luminous radio halos ¹⁵. A radio-mini halo is at the center of the most X-ray luminous cluster RX J1347.5-1145 ¹⁶. Double radio relics have been discovered in ZwCl 2341.1+0000 ¹⁸. Diffuse radio emission has also been detected in this cluster along the optical filament of galaxies shown here by dashed contours ¹⁹.

of continuum radio surveys such as the NVSS ¹¹. It emerged that the non-thermal plasma emitting at radio wavelengths could be not a common property of galaxy clusters (see ¹² and references therein). It was also found that a common feature of intracluster radio sources is a steep synchrotron spectral slope ($\alpha \gtrsim 1$ ^{a,13}). Based on the observed difference in other physical properties (e.g. position in the host cluster, size and morphology) a working classification with three main classes of intracluster radio sources was soon adopted ¹⁴:

- *radio halos* are extended ($\gtrsim 1$ Mpc) sources that have been detected at the centre of merging clusters. Their morphology is similar to the X-ray morphology of the cluster (Fig. 1, left panel);
- *radio mini-halos* are smaller sources ($\lesssim 500$ kpc) located at the centre of cool-core clusters. They surround a powerful radio galaxy (Fig. 1, middle panel);
- *radio relics* have extensions similar to halos and are also detected in merging clusters, but they are usually located in the cluster outskirts and have an elongated morphology (Fig. 1, right panel). In some clusters double relics have been detected (see ^{17,18} and references therein).

The discovery of a non-thermal intracluster component through radio observations has opened a number of astrophysical questions: How do cosmic rays and magnetic fields originate within the intracluster volume? Are all the clusters hosting a non-thermal component? How does it affect the thermodynamical evolution and the mass estimates of galaxy clusters? As detailed in the following sections, new observational facilities will allow us to address most of these open questions in the next few years.

3 Non-thermal component of galaxy clusters: the known and unknown

3.1 Magnetic fields

The intensity of intracluster magnetic fields can be measured ^{20,4}:

^a $S(\nu) \propto \nu^{-\alpha}$

- through Faraday rotation measures (RM) of polarized radio sources within / behind clusters (current measurements: $\sim 1\text{--}10 \mu\text{Gauss}$);
- by comparing synchrotron radiation from diffuse radio sources with non-thermal HXR emission due to Inverse Compton (IC) scattering of CMB photons by relativistic electrons (current measurements: $\sim 0.1\text{--}0.3 \mu\text{Gauss}$);
- by assuming energy equipartition between intracluster CRs and magnetic fields (current measurements: $\sim 0.1\text{--}1.0 \mu\text{Gauss}$);
- through the study of cold fronts in merging galaxy clusters (current measurements: $\sim 10 \mu\text{Gauss}$).

The discrepancy between these different measurements can indeed be related to the complex structure of intracluster magnetic fields. Magnetic field models where both small and large scale structures coexist must be considered, as recently shown by joint observational and numerical studies (e.g. ^{21,22}). A radial decline of the magnetic field strength has also been observed in agreement with different magneto-hydrodynamic simulations (^{23,24} and references therein). This can have important consequences in comparing, for instance, volume averaged magnetic field measurements (such as those obtained through the equipartition and IC methods) with RM estimates, that are very sensitive to local variations in the magnetic field and ICM structure. Consistent magnetic field measurements have been recently obtained in Coma by firstly determining a model of magnetic field strength, radial profile and power spectrum, and then deriving with the different methods an average magnetic field strength over the same cluster volume ²³. Finally, magnetic field measures based on IC scattering of CMB photons have also to take into account the controversial detection of HXR flux from galaxy clusters (Sect. 3.3) and that radio ($\approx 1.4 \text{ GHz}$) and XHR ($\approx 50 \text{ keV}$) radiations come from different populations of intracluster relativistic electrons ²⁰.

Magnetic fields at the observed intensity level ($\approx 1 \mu\text{Gauss}$) could result from amplification of seed fields through adiabatic compression, turbulence and shear flows associated to the hierarchical structure formation process. Seed fields could have been created by primordial processes and thus fill the entire volume of the universe, or through different physical mechanisms, such as the “Biermann battery” effect in merger and accretion shocks, or the outflow from AGN and starburst galaxies in proto-clusters at $z \approx 4 - 6$ (see ²⁵ for a recent review).

3.2 Cosmic rays

Different mechanisms can produce CRs in galaxy clusters. Primary relativistic particles can be accelerated by processes internal to cluster galaxies, i.e. galactic winds or AGNs, and then ejected into the intracluster volume. Intracluster CRs gyrate around magnetic field lines which are frozen in the ICM. The expected diffusion velocity of relativistic particles being of the order of the Alfvén speed ($\sim 100 \text{ km/s}$), CRs need $\gtrsim 10 \text{ Gyr}$ to propagate over radio halo and relic extensions. The radiative lifetime of relativistic electrons is however much shorter ($\lesssim 0.1 \text{ Gyr}$) due to IC and synchrotron energy losses. Therefore CRs cannot simply be ejected by active galaxies and propagate over the cluster volume, but they have to be continuously (re-)accelerated *in situ* ²⁶. Electrons can be (re-)accelerated to GeV energies by shocks and turbulence generated by major cluster mergers, and to TeV energies at the strong accretion shocks ²⁷, where cold infalling material plunges in the hot ICM of massive galaxy clusters and shock Mach numbers range between 10 and a few 10^3 (see Fig. 2).

The timescales for energy losses as well as the diffusion timescales are instead longer than the Hubble time for CR protons (CRps). They thus can be continuously accelerated both by internal and by external processes, resulting in an effective accumulation of relativistic and

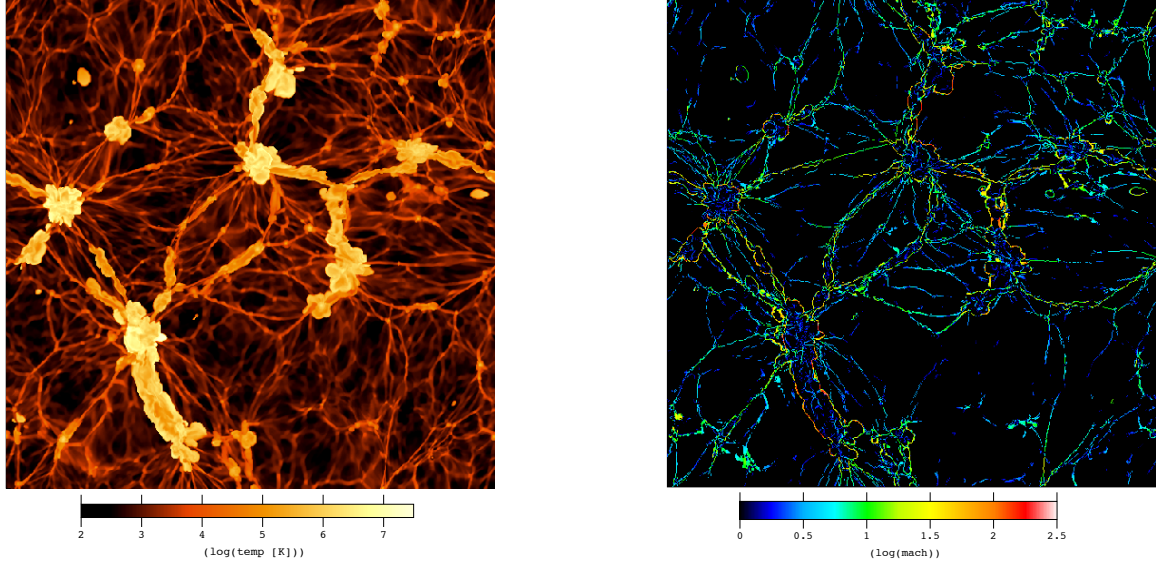


Figure 2: Simulated maps of the gas temperature (left) and Mach number (right) in a region of side 80 Mpc (from²⁹). Accretion shocks (due to large scale matter infall on massive clusters) have significantly higher Mach numbers compared to shocks that develop in the central regions of major merging clusters. Accretion shocks are expected to be highly efficient sources of particle acceleration, with steeper spectra of injection compared to the shocks internal to clusters.

ultra-relativistic CR ps in clusters. Hadronic CRs can subsequently produce Gamma-rays and secondary relativistic electrons through inelastic collisions with the ions of the ICM (see e.g.²⁸ and references therein). Other possible physical mechanisms that could accelerate electrons up to ultra-relativistic energies (TeV–PeV) are related to interactions of CMB photons with ultra-relativistic CR ps ³⁰, and/or very high energy intracluster Gamma-ray photons³¹. Dark matter annihilation can also be a source of secondary relativistic electrons and positrons³².

Relativistic electrons observed at radio wavelengths can thus have a secondary origin³³, and/or have been (re-)accelerated by ICM shocks and turbulence developed during cluster mergers^{34,35}. Current radio observational results are mostly in agreement with this latter hypothesis (e.g.³⁶). The strongest point leading to this conclusion is the fact that giant radio halos and relics have been detected up to now only in merging clusters. However, as detailed in Sect. 3.3, deeper radio, Gamma-ray and HXR observations are required to get firm conclusions about the origin of intracluster CR es .

At the light of current results different questions still need to be answered. First of all we have to understand if relativistic electrons are really hosted *only* in merging systems (as present radio observations suggest) or if *all* clusters have a radio halo/relic. In addition extended radio sources have not been detected in *all* merging clusters. If shocks and turbulence related to cluster mergers are the mechanisms responsible for electron re-acceleration, the absence of observational evidence of intracluster CR es in several merging systems could be related to other physical effects. The observed correlation between radio power and cluster mass seems to indicate that only very massive cluster mergers are energetic enough to accelerate electrons at relativistic velocities in the intracluster volume¹². This scenario needs however to be tested through higher sensitivity radio observations, since the non-detection of radio halos/relics in many merging clusters could be related to a lack of sensitivity of current instruments. Deep future radio surveys (Sect. 4) will allow us to study the evolution of the luminosity function of radio halos, giving important constraints on current models for electron acceleration in galaxy clusters³⁷.

Table 1: The non-thermal “Pandora’s vase” for galaxy clusters. We can expect multi-wavelength emission and particle acceleration from different kinds of interactions between: **(first row)** intracluster magnetic fields, CMB photons and ICM ions, and **(first column)** relativistic / ultra-relativistic cosmic rays accelerated by different possible physical mechanisms in galaxy clusters (see Sect. 3.2). Note in addition that the interaction between CMB photons and intracluster Gamma-ray photons can produce ultra-relativistic CRs.

&	MAGNETIC FIELDS	CMB PHOTONS	ICM IONS
REL. CR _e s	Radio emission (Synchrotron)	Hard X-rays (Inverse Compton)	
REL. CR _p s			Gamma-rays + Secondary CRe (Hadronic collisions)
ULTRA-REL. CR _e s	Hard X-rays (Synchrotron)	Gamma-rays (Inverse Compton)	
ULTRA-REL. CR _p s		Ultra-rel. CR _e s (Bethe-Heitler)	

3.3 A multi-wavelength view of the non-thermal intracluster component

An increasing number of theoretical and numerical analyses (e.g. ^{38,39}) are exploring the possibility that a combination of CR protons and electrons of primary and secondary origin can reproduce the multi-wavelength radiation of the non-thermal intracluster component. Besides synchrotron radio emission from GeV electrons and intracluster magnetic fields, we can expect (see also Table 1):

- *HXR emission* from IC scattering of CMB photons by GeV electrons or from synchrotron emission of TeV electrons;
- *Gamma-ray emission* from IC scattering of CMB photons by TeV electrons or from inelastic collision of CR_ps with the ions of the CMB.

Radio synchrotron emission from galaxy clusters is now firmly confirmed (Sect. 2). Evidence of non-thermal (IC) HXR emission from several clusters hosting diffuse radio sources has been obtained mostly through the X-ray satellites *Beppo-SAX* and *RXTE* (e.g. ^{40,41}). The detection and nature (thermal or non-thermal) of the HXR excess in galaxy clusters is however strongly debated (⁴² and references therein). Up to now, only upper-limits have been derived for the Gamma-ray emission of galaxy clusters, which imply a CR energy density less than 5-20% of the thermal cluster energy density. If we assume intracluster magnetic fields of the order of μ Gauss (Sect. 3.1) and cluster radii of a few Mpc, it can easily be derived that intracluster CR and magnetic field energy densities are not far from equipartition ⁴³.

4 Perspectives

In order to make a proper comparison between observational results and current theoretical models about the origin and physical properties of the non-thermal intracluster component, we

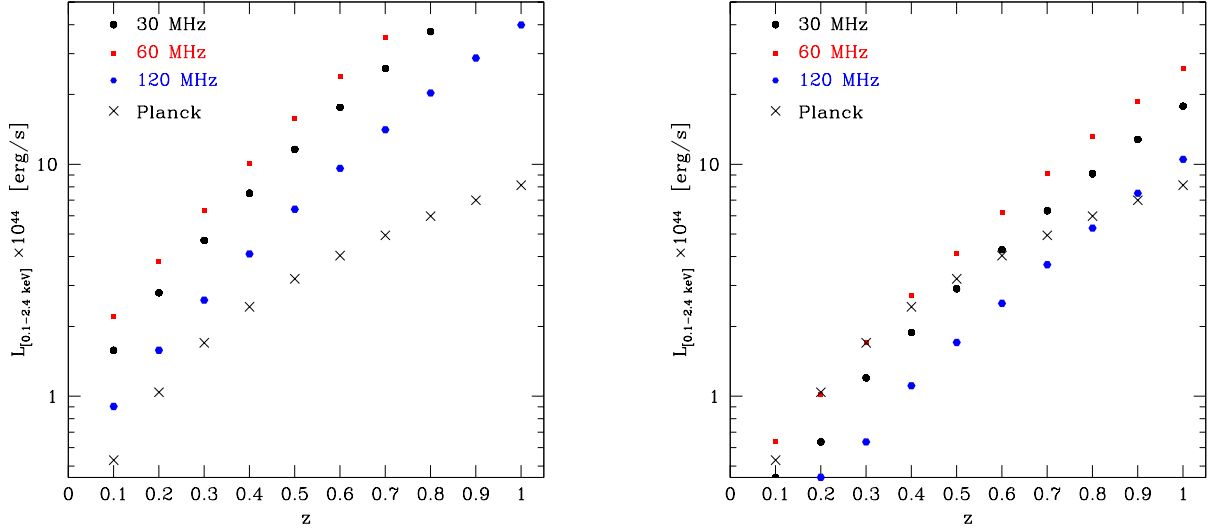


Figure 3: Evolution with redshift of the X-ray luminosity limit of clusters whose diffuse radio emission can be detected with *LOFAR* at 30, 60 and 120 MHz down to the sensitivity limit of the All-Sky Survey (left) and Deep Survey (right), at a resolution of 21 arcsec, assuming to detect at least 50% of the radio flux at 10σ level (our estimates). The detection limits expected for the *Planck* cluster catalogue are shown with black crosses (courtesy of A. Chamballu and J. Bartlett).

need multi-frequency observations of *statistical* samples of clusters hosting diffuse radio sources. The study of galaxy cluster SED^b from Gamma-rays to low radio frequencies, for instance, is essential to discriminate between the different particle acceleration scenarios and to improve the measure of magnetic field intensity (see e.g. ⁴⁴).

In the next decades several radio facilities – such as *LOFAR*, *LWA*, *ASKAP*, *MeerKAT* and, last but not least, *SKA* – will allow to significantly improve our knowledge about the radio emission of the non-thermal intracluster component (e.g. ⁴⁵). We are now assisting to the opening of a spectral window largely unexplored by previous radio telescopes ($\nu < 200$ MHz) thanks to *LOFAR*. Due to the steep synchrotron spectrum of halos and relics, the detection of diffuse cluster radio sources is favored at this low frequencies (see Fig. 7 in ²). The planned *LOFAR* All-Sky survey is expected to detect about 350 radio halos at redshift $z \lesssim 0.6$ ⁴⁶.

At other wavelengths and based on what detailed in previous sections, important constraints about the non-thermal cluster emission are expected from the Gamma-ray *Fermi* satellite, and from telescopes observing in the HXR band, such as *NuSTAR* and, possibly, *IXO* (e.g. ³⁹). The detection of statistical samples of radio halos and relics through on-going and up-coming radio surveys (e.g. “K.P. Extragalactic Surveys” of *LOFAR*⁴⁷, “EMU” survey of the *ASKAP* telescope^c) will need complementary multi-frequency projects for:

- obtaining complementary cluster catalogs to verify the presence of galaxy clusters corresponding to diffuse radio sources (see for instance the nice complementarity between the clusters that could be detected with *LOFAR* All-Sky and Deep Surveys and with *Planck*, Fig. 3);
- getting a precise physical characterization of the detected cluster – and in particular of its redshift, mass and dynamical state – in order to test current models of CR acceleration.

^bSpectral Energy Distribution

^c<http://www.atnf.csiro.au/people/rnorris/emu/>

To conclude, after the huge progress in the last fifteen years of our knowledge of the evolutionary physics of cluster galaxies and of the thermal ICM, we are now living in the “golden age” for non-thermal cluster studies: the opening of the few spectral windows largely unexplored by astronomical observations (i.e. the HXR, Gamma-ray and low-frequency radio bands) will allow us to study the non-thermal physics of galaxy clusters with unprecedented statistics and thoroughness.

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